Deterministic Greedy Routing with Guaranteed Delivery in 3D Wireless Sensor Networks

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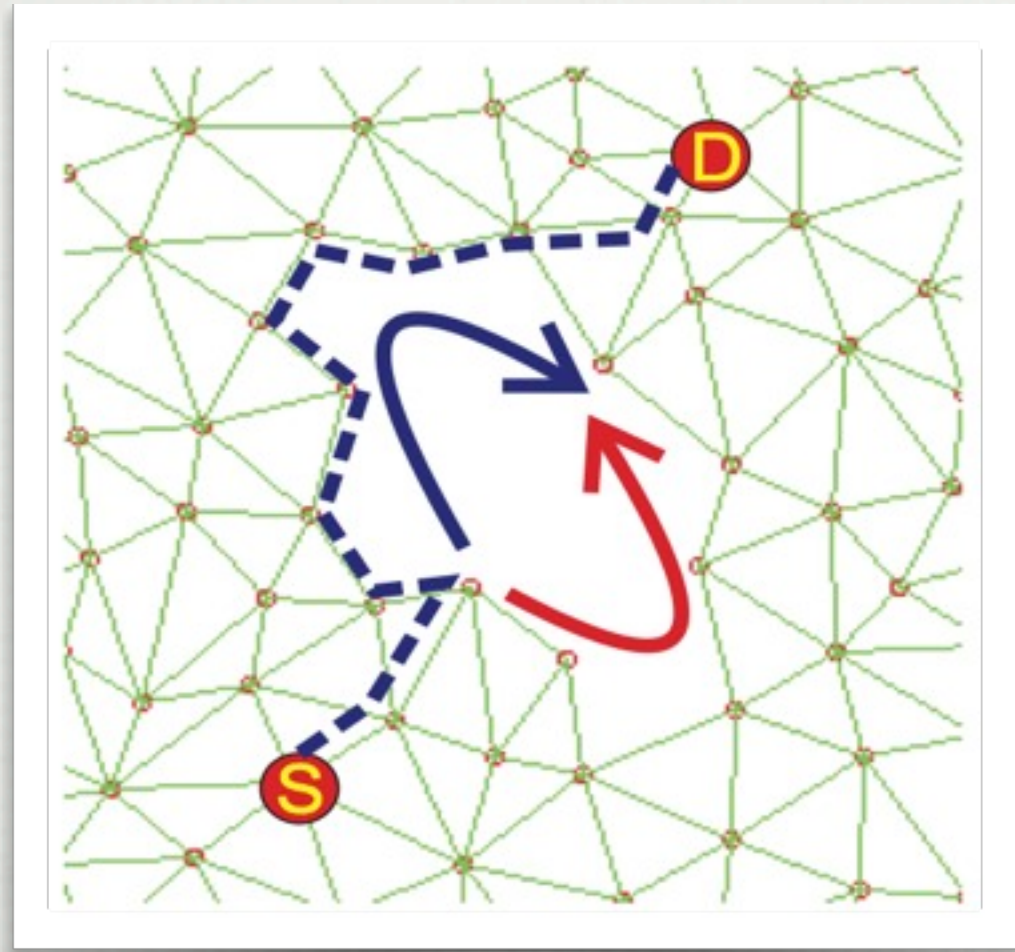
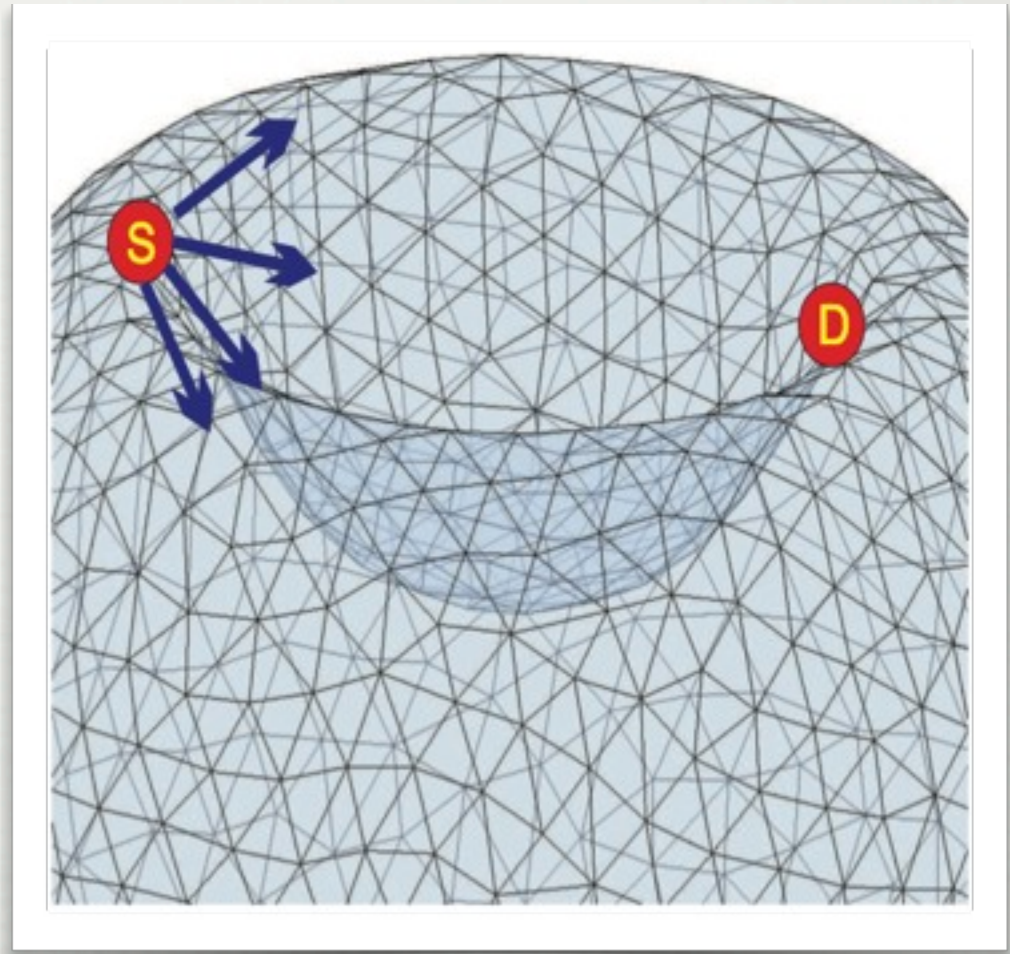
GREEDY ROUTING

- What is greedy routing?
  - A node always forwards a packet to one of its neighbors, which is the closest to the destination of the packet
- Why greedy routing?
  - Both computation complexity and storage space bounded by a small constant
  - Scalable to large networks with stringent resource constraints on individual nodes

LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Face routing (alternatives/enhancements) [13-20]
  - Exploit the fact that a void in a 2D planar network is a face with a simple line boundary





LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Greedy embedding [21-27]
  - Provides theoretically sound solutions to ensure the success of greedy routing
  - Unfortunately, none of the greedy embedding algorithms can be extended from 2D to general 3D networks
- More challenges revealed in [28]
  - There does not exist a deterministic algorithm that can guarantee delivery based on local information only in 3D networks

LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Recovery from failures in 3D greedy routing
  - Project to a 2D plane to apply face routing [4,5]: no guarantee (face routing on projected plane does not ensure a packet to actually move out of void in the original 3D network)
  - GDSTR-3D [8]: If a local minimum is reached, forward packet along a spanning tree. Deterministic, but not truly greedy (a node must maintain a set of convex hulls, requiring a storage space proportional to network size)
  - Local searching [3,6]: jump out a local minimum. Greedy, but non-deterministic.

OUR MAIN CONTRIBUTIONS

- To our best knowledge, this is the first work that realizes deterministic greedy routing in 3D networks
  - Truly greedy: both computation complexity and storage space bounded by a small constant
  - Deterministic and guaranteed: proved guarantees on packet delivery between any pair of nodes
- Conflicts with [28]? No.
  - Rely on a distributed preprocessing (mapping) that intrinsically utilizes non-local information
  - After preprocessing, a node needs constant storage and computation to make local routing decisions

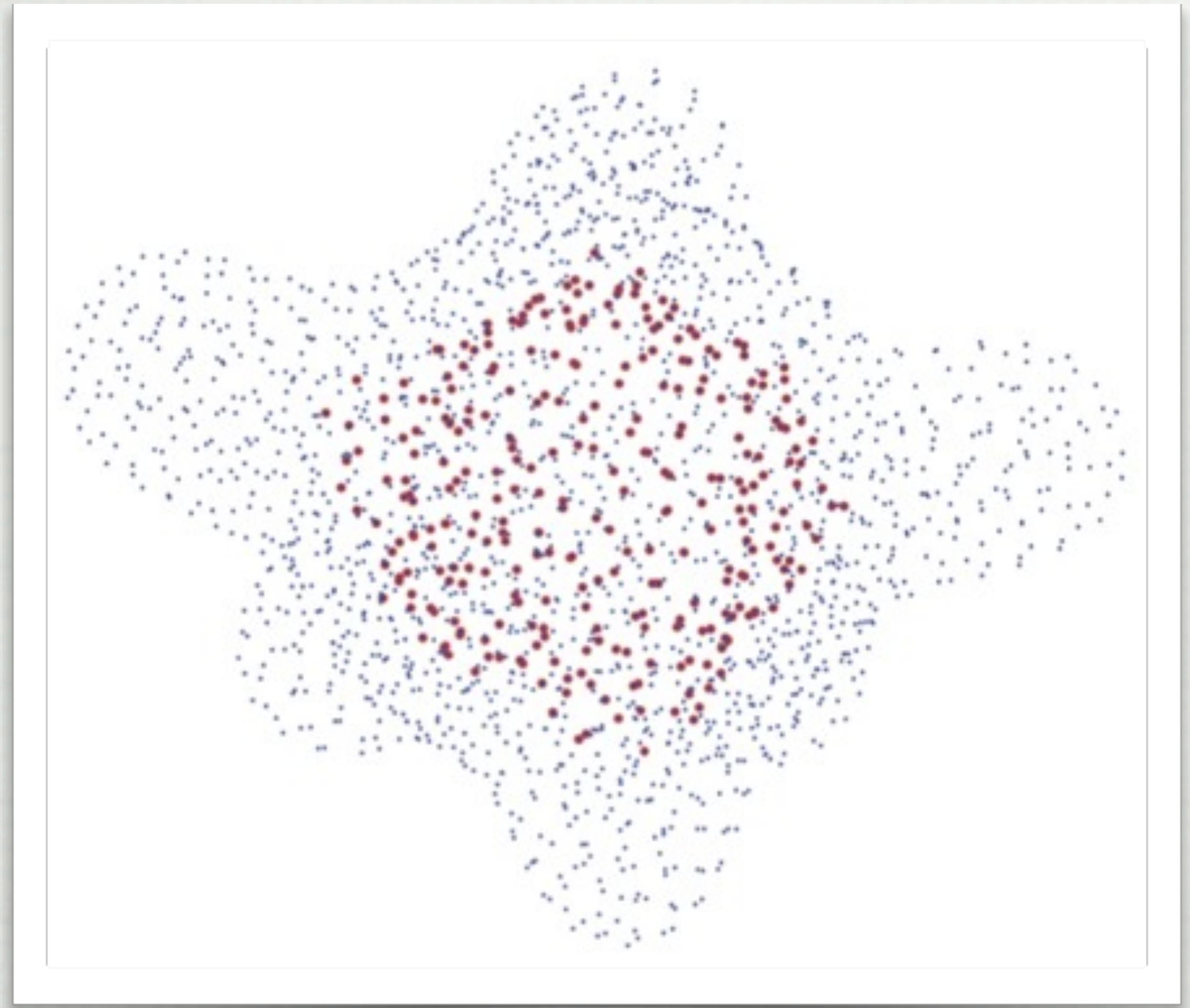
GREEDILY REACHABLE NETWORK

- Greedily Reachable: Node i is greedily reachable to Node j if a packet can be greedily routed from the former to the latter based on a metric that is kept locally and consumes constant storage space and computing power
- Greedily Reachable Network: a network is called a greedily reachable network if every two nodes in the network are greedily reachable to each other
- We aim to map a general 3D sensor network to a greedily reachable network

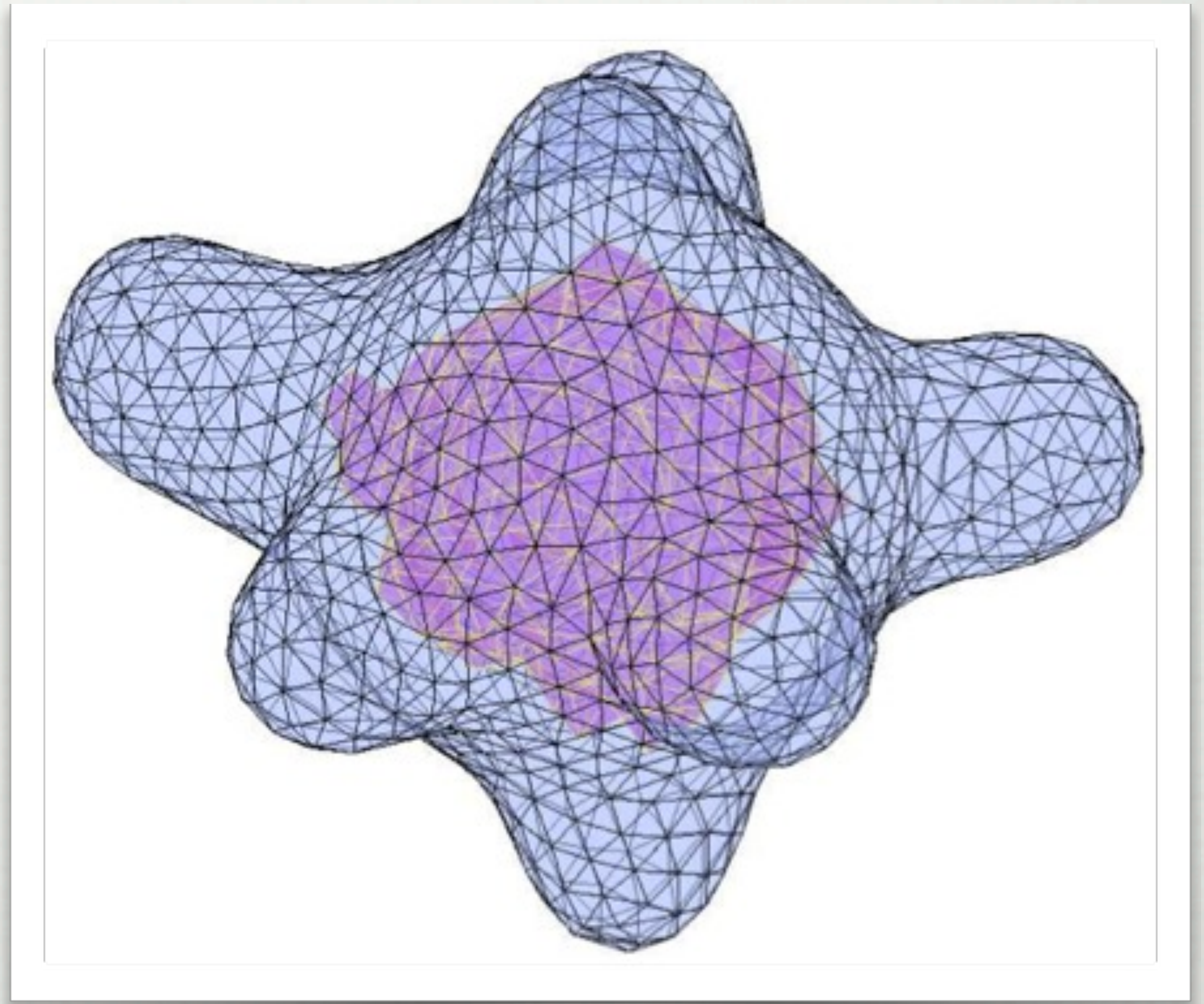
DEFINITIONS

- Unit Tetrahedron Cell (UTC):
  - A tetrahedron formed by four network nodes, which does not intersect with any other tetrahedrons.
  - A simple algorithm to construct the UTC mesh structure (requires a local coordinates system by using estimated local distance [30])

UNIT TETRAHEDRON CELL (UTC)



Original Network



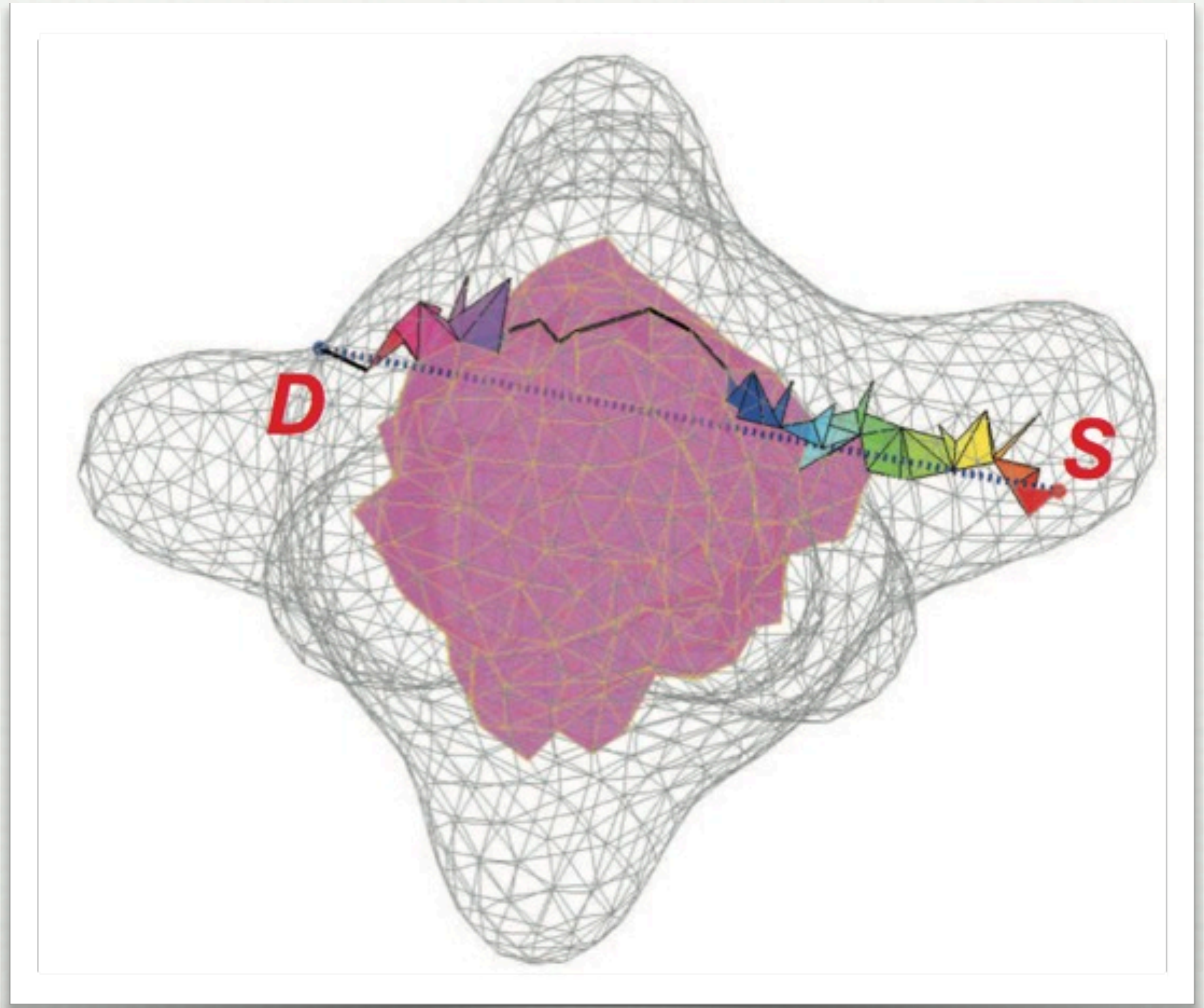
UTC

DEFINITIONS

- Neighboring UTCs: two UTCs are neighbors if and only if they share a face.
- Boundary Face: a face is a boundary face if it is contained in one UTC only.
- Boundary UTC: a UTC is a boundary UTC if it contains at least one boundary face. A non-boundary UTC is called an internal UTC.
- Hole of a Network: a hole of a network is formed by a closed surface that consists of boundary faces. The space outside the network is considered as a special hole, forming the outer boundary.

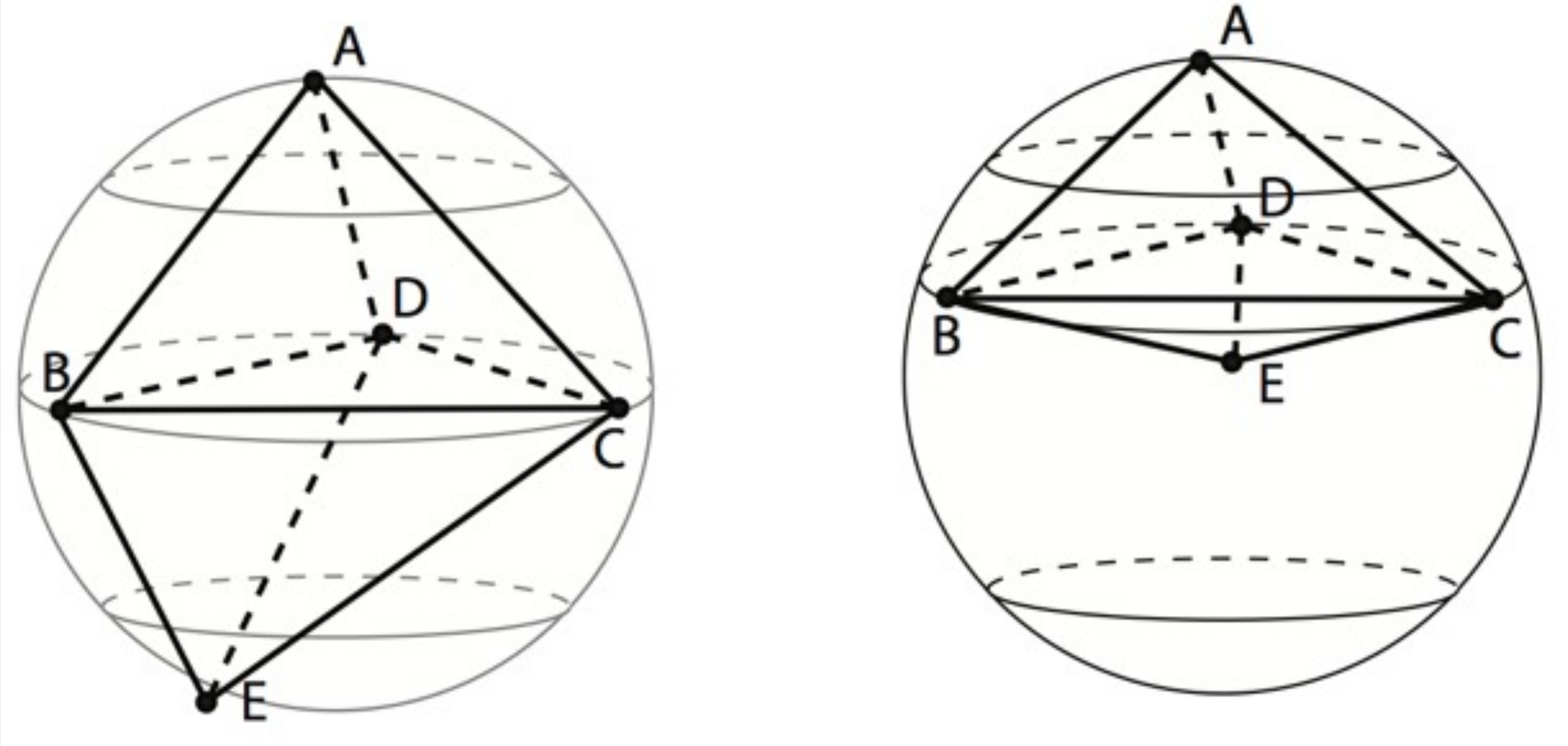
ROUTING

- ☐ Routing at internal UTCs and boundary UTCs



ROUTING AT INTERNAL UTCS

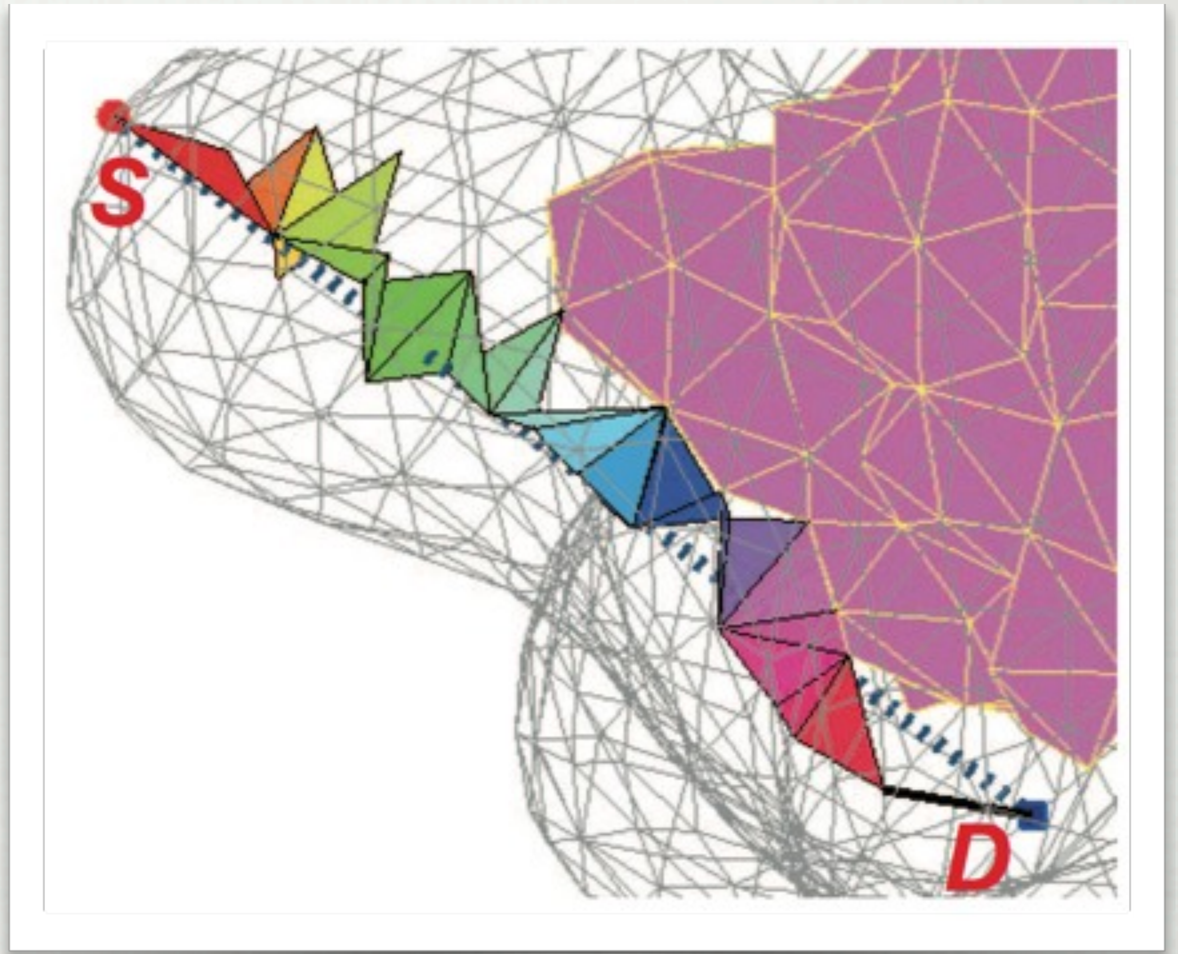
- Anti-intuitively nontrivial: node-based greedy routing is not always successful
- Delaunay unit tetrahedron cell (DUTC): a UTC whose circumsphere contains no other nodes except its vertices



(a) DUTC. (b) Non-DUTC.

ROUTING AT INTERNAL UTCS

- Our solution: face-based
  - G denotes a line segment from source to destination
  - G passes through a set of UTCs, and intersects with a sequence of faces.
  - Data packet is forwarded to the neighboring face which is closer to the destination.
- Lemma 1: face-based greedy routing does not fail at any non-boundary UTC.



ROUTING AT BOUNDARY UTCS

- Face-based greedy routing algorithm supports greedy data forwarding at internal UTCs.
- However, it may fail at boundaries, with possible complex shapes.
- Map a boundary to a sphere?

ROUTING AT BOUNDARY UTCS

- Mapping only the boundary to a sphere is NOT sufficient!
  - The virtual coordinates for boundary nodes would become inconsistent with the coordinates of the internal nodes.
  - A node cannot identify the correct target on the boundary, in order to advance the packet to its destination.
- A continuous volumetric mapping under spherical boundary condition is imperative!

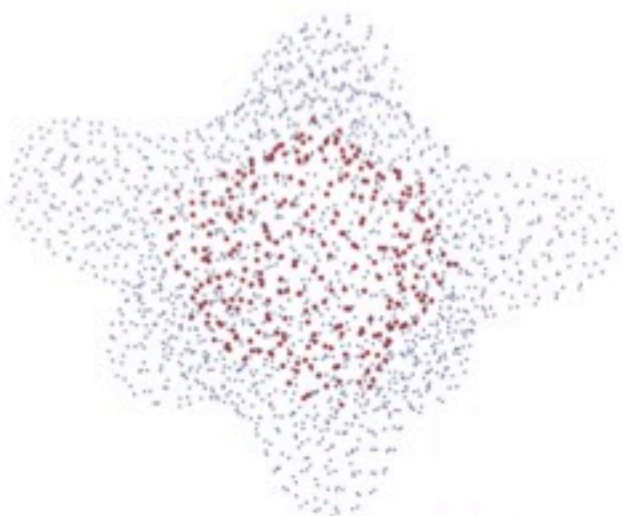
ROUTING AT BOUNDARY UTCS

- Theory - Harmonic Function:
  - In general, a function f is harmonic if it satisfies the Laplace's equation $\triangle f = 0$.
  - If Dirichlet boundary condition is imposed on this partial differential equation, a harmonic function is the solution of the Dirichlet's problem.
- Volumetric Harmonic Function:
  - A map between the original volumetric data and a canonical domain in R^3.
  - In our case, the canonical domain is a ball in order to support greedy routing.

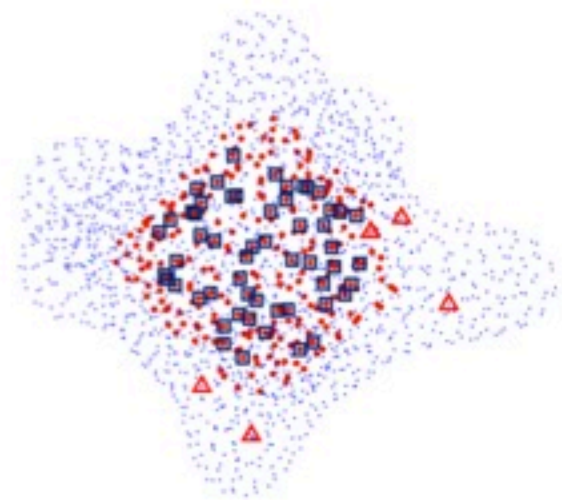
ROUTING AT BOUNDARY UTCS

- How to do the mapping?
  - Spherical harmonic map: first map the boundary of the 3D network continuously and one-to-one to a unit sphere by minimizing spherical harmonic energy
  - Volumetric harmonic map: next minimize the volumetric harmonic energy under the spherical boundary condition computed in the first step
- We design distributed algorithms to realize such mapping
  - Both algorithms are distributed; a node needs to communicate with its one-hop neighbors only
  - Lemma 2: The iterative algorithms are proved convergent
  - The number of iterations is $O(n^2)$

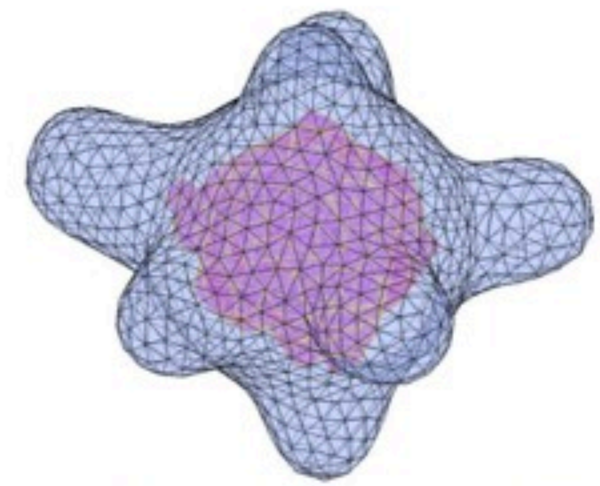
ROUTING



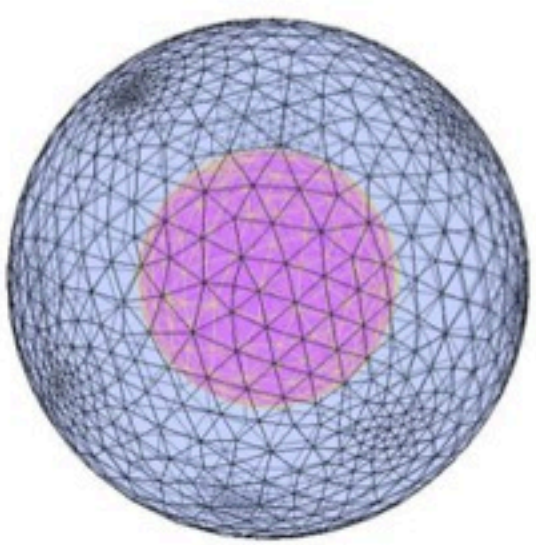
(a) A 3D sensor network (Network model 1).



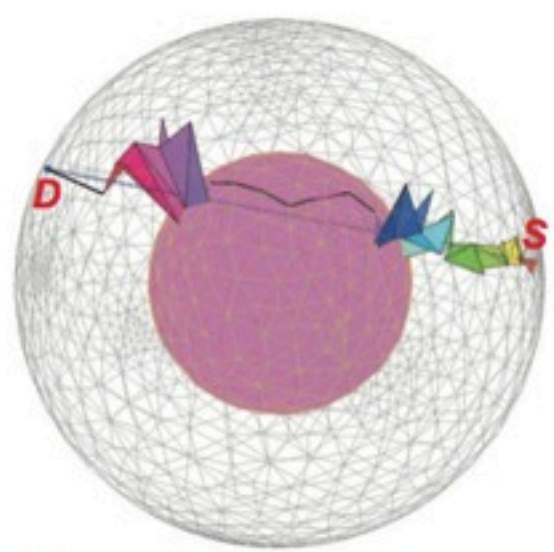
(b) Local minimums in nodal greedy routing.



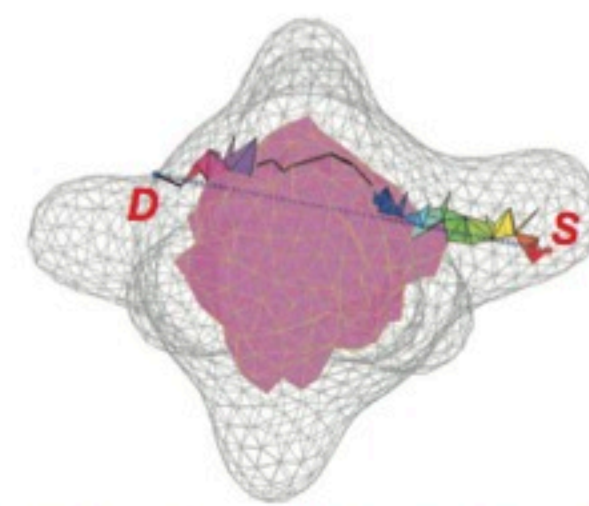
(c) Unit tetrahedron cells (UTCs).



(d) Volumetric Harmonic mapping.



(e) A greedy routing path in mapped domain.



(f) A greedy routing path in original network.

ROUTING

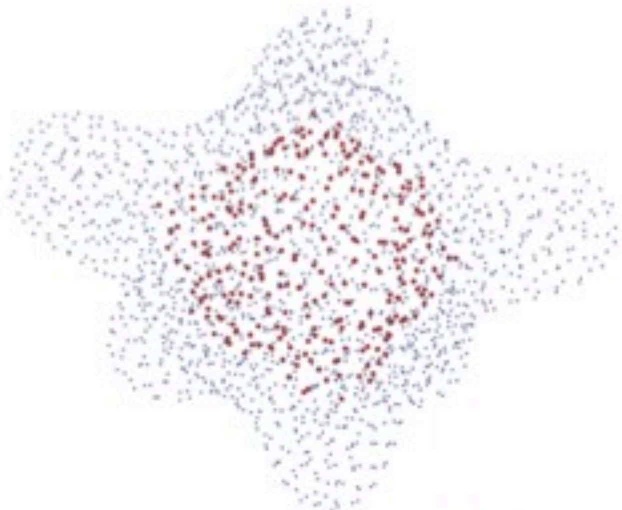
- After mapping, each node has its virtual coordinates in 3D space where boundaries have been mapped to spheres
- Apply face-based greedy routing if next face is reachable
- When fails to find the next face toward destination

  => the packet must arrive at a boundary

  => greedy routing based on virtual coordinates is applied to move the packet across the void area

  => face-based greedy routing is applied again whenever next face becomes reachable (i.e., local min resolved)
- Repeat until reach the destination

ROUTING



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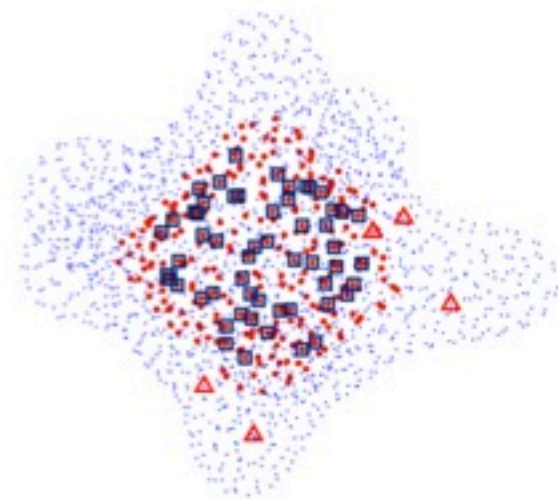

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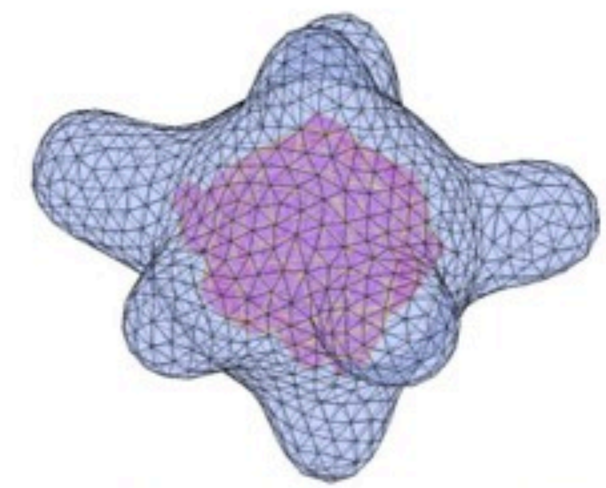

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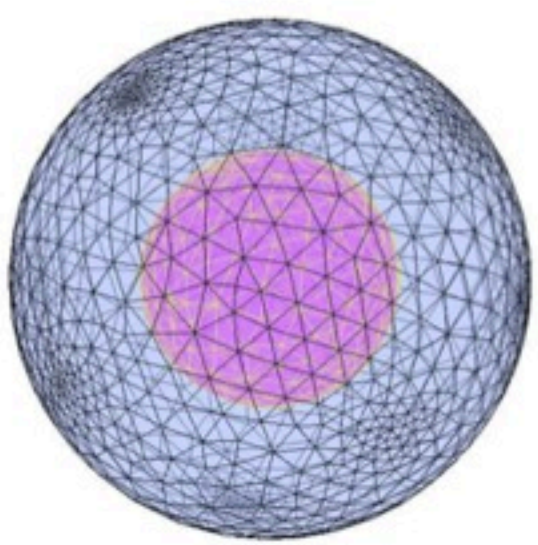

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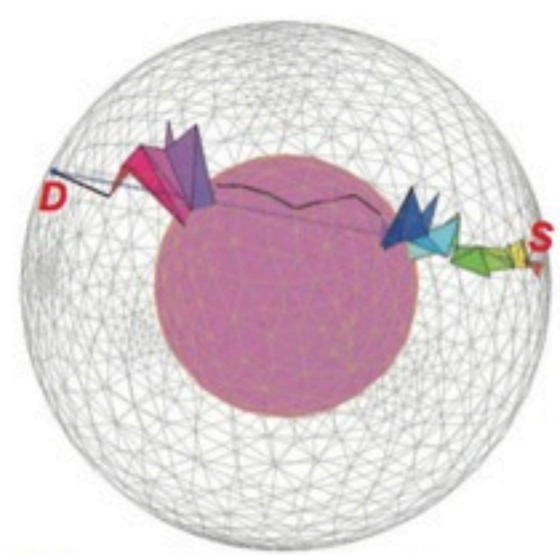

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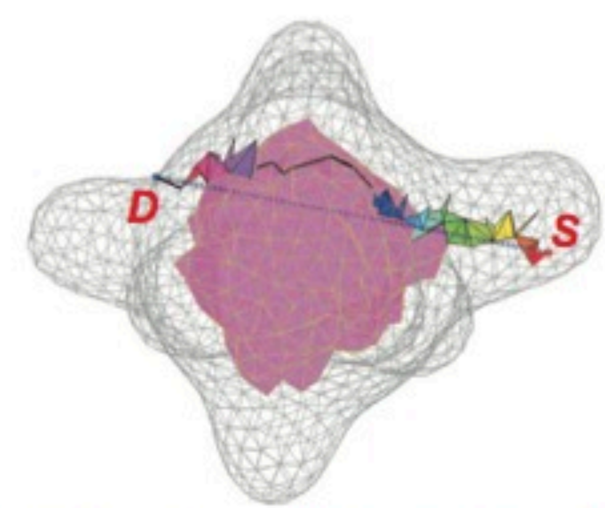


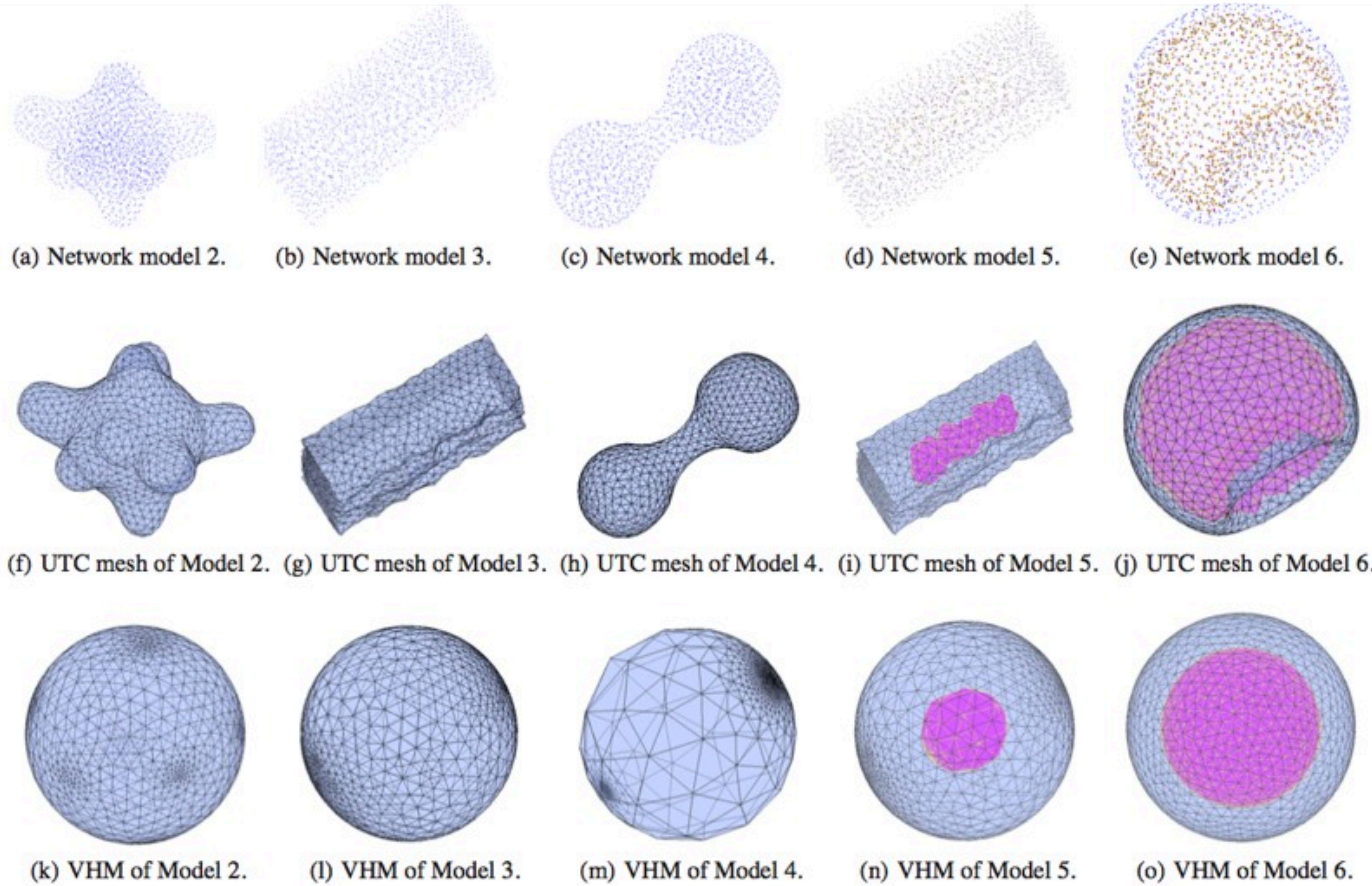
(f) A greedy routing path in original network.

SIMULATIONS: PEER-TO-PEER ROUTING

- 3D sensor networks in different sizes (ranging from 1,000 to 2,500) and shapes are simulated
- Compared with [6]
- Performance metrics:
  - Delivery ratio: guarantee 100% packet delivery
  - Stretch factor (the ratio of the actual path length to the shortest path length)

[6] R. Flury and R. Wattenhofer, "Randomized 3D Geographic Routing," in *Proc. of IEEE INFOCOM*, pp. 834–842, 2008.

SIMULATIONS: PEER-TO-PEER ROUTING



(a) Network model 2. (b) Network model 3. (c) Network model 4. (d) Network model 5. (e) Network model 6.

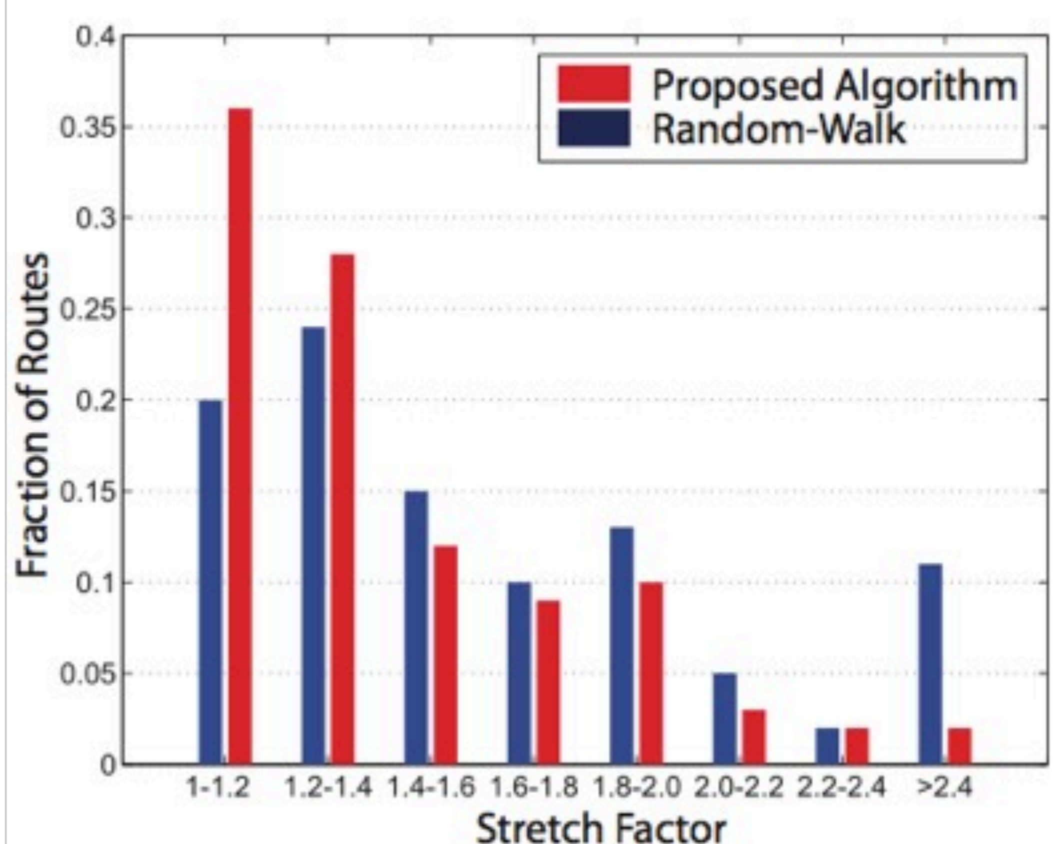
(f) UTC mesh of Model 2. (g) UTC mesh of Model 3. (h) UTC mesh of Model 4. (i) UTC mesh of Model 5. (j) UTC mesh of Model 6.

(k) VHM of Model 2. (l) VHM of Model 3. (m) VHM of Model 4. (n) VHM of Model 5. (o) VHM of Model 6.

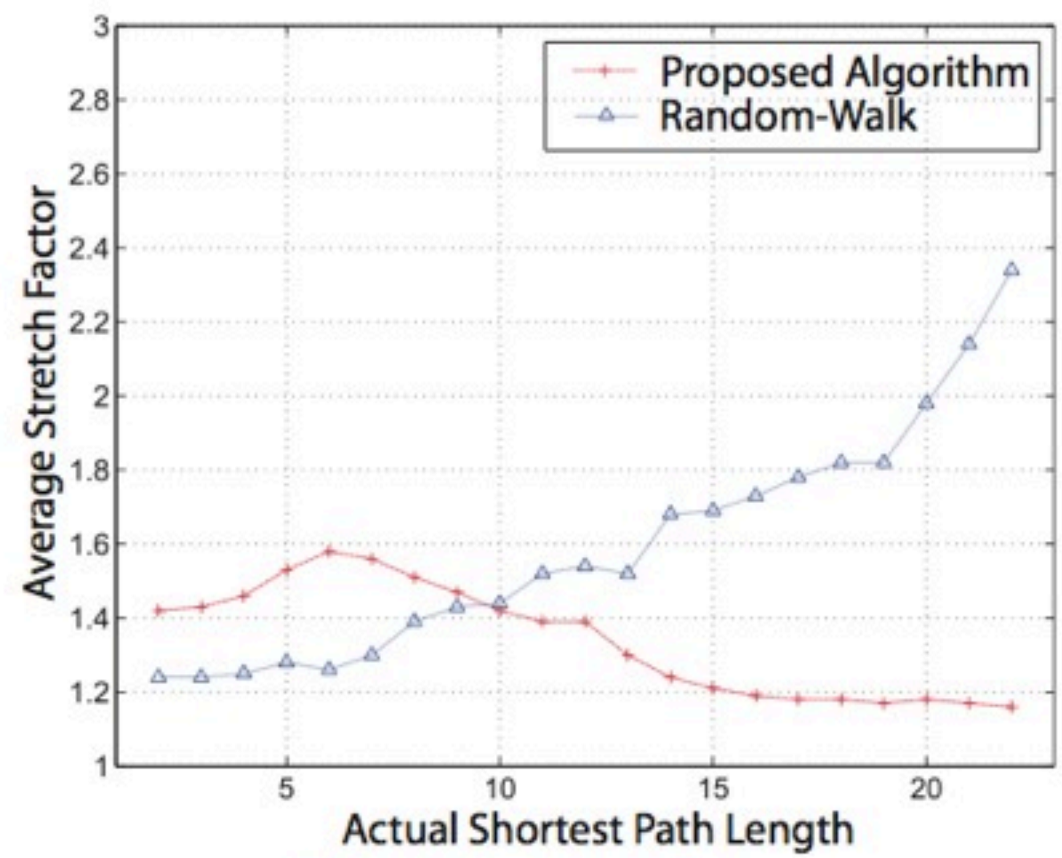
SIMULATIONS: PEER-TO-PEER ROUTING

- Stretch factor

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Overall Average
Proposed Algorithm	1.63	1.63	1.66	1.61	1.62	1.44	1.59
Random-Walk [6]	1.83	1.70	1.73	1.84	1.89	2.12	1.85



(a) Stretch factor distribution.



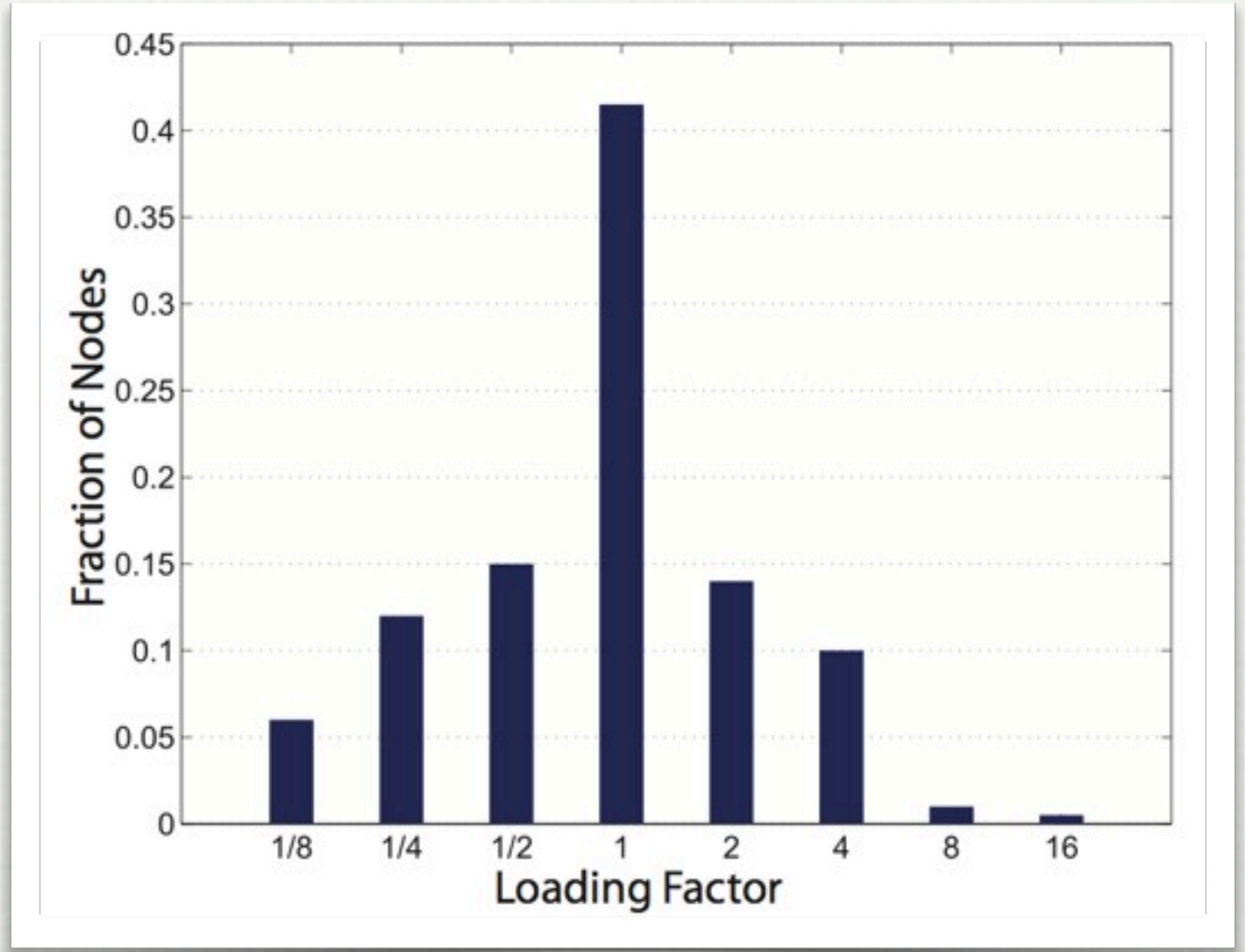
(b) Impact of path length.

SIMULATIONS: DATA STORAGE AND RETRIEVAL

- The network consists of tetrahedrons and is mapped into a unit sphere in a 3-D space
- Uniformly map data to points inside of the unit sphere
- Greedy routing is applied for data storage and retrieval

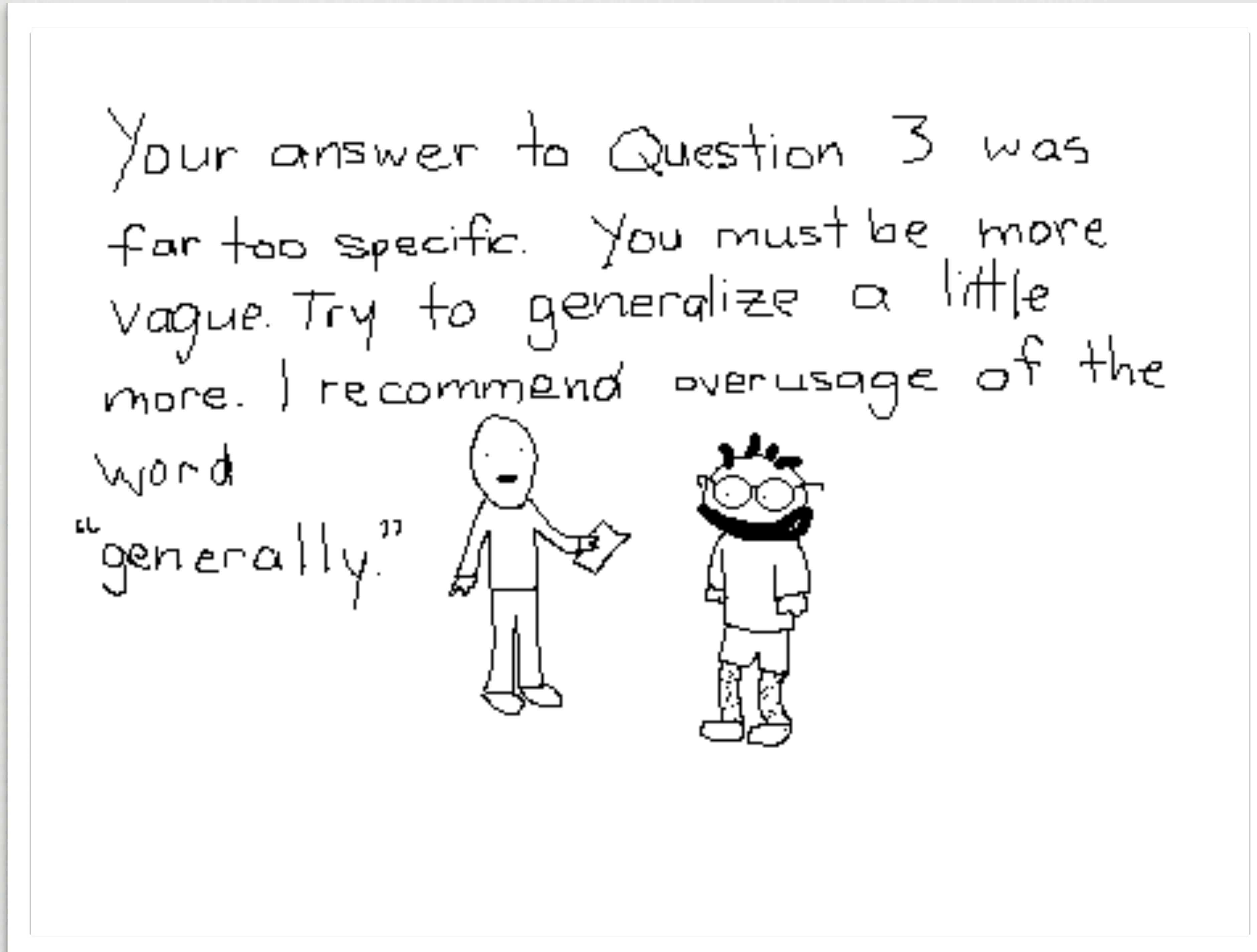
SIMULATIONS: DATA STORAGE AND RETRIEVAL

- To insert 10,000 data generated by a set of randomly chosen nodes



CONCLUSION

- Investigate greedy routing in 3D wireless sensor networks
- Propose a greedy routing algorithm
  - Construct UTC mesh
  - Face-based greedy routing for internal UTCs
  - Volumetric Harmonic mapping for boundary UTCs
- Limitations and future work
  - Needs segmentation for a network with multiple holes
  - Volumetric Harmonic mapping becomes less efficient (i.e., higher stretch) under extreme boundary condition (e.g., an extremely narrow or thin network)


Your answer to Question 3 was far too specific. You must be more vague. Try to generalize a little more. I recommend overusage of the word "generally."

QUESTIONS ?